STUDIES ON RELIABLE AND ENERGY-EFFICIENT WIRELESS SENSOR NETWORKS FOR MOBILE HEALTHCARE SYSTEMS

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by

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STUDIES ON RELIABILE AND ENERGY-EFFICIENT WIRELESS SENSOR NEWOTKRS FOR MOBILE HEALTHCARE SYSTEMS

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The outstanding improvement of communication and sensor technologies has not brought us only convenience to our lives but also envisioning our promising future with no barrier. Real-time information gathering, processing and communication in sensor networks have enriched people's lifestyles as they never imagined before. Wireless sensor networks (WSN) have provided people so much convenience with its variable applications such as environmental monitoring, human-centric applications, military applications, support for logistics, and etc. Most of all, researches on wireless body area networks (WBAN) have been revisited frequently for ubiquitous and affordable healthcare as healthcare related products and applications have obtained great attention for the people who are really concerned about their health, fitness as well as well-being lives.

First, this dissertation examines true optimal routing with use of a novel load balancing aware routing algorithms for multipath wireless sensor networks. We propose an innovative multipath routing network design scheme utilizing dynamic load-balancing aware feedback control system that can predict future traffic flow with preloaded traffic control. Then, we narrow down to wireless body area networks applying linear network coding design approach in both network and MAC layers. Through a discussion of the analysis, modeling, implementation, and simulation, we derive the solutions for the proposed designs that can significantly improve the

reliability and energy-efficiency of the desired healthcare related systems.

BIOGRAPHICAL SKETCH

Daniel Seung Lee received his B.S. degree in Computer Engineering from Washington State University, Pullman, WA in 1994. He received his M.S. degree in Electrical Engineering from Columbia University, New York, NY in 2005. After he came to Cornell University, he became so much interested in Wireless Sensor Networks, Mobile Ad-Hoc Networks, Wireless Body Area Networks, Routing Protocol, and Network Coding. He joined Wireless Intelligent Systems Lab. (WISL) and worked with Dr. Stephen B. Wicker.

Daniel Seung Lee's research interests are Coding Based Routing Protocols, Wireless Sensor Networks, and Mobile Ad Hoc Networks. The main topic of his research is reliable and energy-efficient design strategy in wireless body area networks, which can be applied to healthcare systems.

This document is dedicated to my wife, Helen and two daughters, Cindy and Chelsea that have always let me realize why I live.

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CHAPTER 1

Introduction

1. 1. Background

1.1.1. Wireless Sensor Networks (WSN) Overview

Wireless networking and communication technologies have obtained great attention over conventional wired networking due to their mobility, convenience of use, and relatively low cost for infrastructure. A variety of multimedia services, which require high data rate transmission as well as better quality of service, have enriched our daily lives with ubiquitous access to wireless communication systems. Wireless sensor networks have played a prominent role in a variety of applications, including habitat monitoring, environmental observation, forecasting system, structure health monitoring, home/office networking, smart energy, transport area security system, etc., [1-9].

However, as the demand for multimedia data increases, limited resources such as the limited battery power and available bandwidth of the wireless sensor platform have posed technical challenges [10]. Robust and energy-efficient routing protocol can be considered as an excellent candidate solution, that has the ability of resolving the limited resource issue in terms of end-to-end delay, throughput, offered load, etc [11-13].

1.1.2. Healthcare and Wireless Body Area Networks (WBAN)

Applications related healthcare have significantly obtained great attention due to the concerns about well-being life and adult diseases. The rate of elderly people's population over 65 years old has been growing tremendously, and adult diseases have become more general and spread to younger generations. People would like to focus more on how they live rather than just how long they live. Consequently, as more demand on the ubiquitous and intelligent healthcare systems have been made, the related infrastructures such as e-health, healthcare practice supported by electronic processes and communication, and m-health, practice of healthcare supported by mobile devices, have been developed more and more.

Wireless sensor network (WSN) applications have been rapidly spread to recent people's lives. With a help of the outstanding development of small sized sensors and low-energy consuming devices, WSN can deeply penetrate into human lives. Furthermore, as people have been significantly concerned with remote monitoring health status throughout sensors placed on or along human body, healthcare business has recently become a major application of WSN [27-29, 31-33].

Wireless body area networks (WBAN) have contributed significantly to the healthcare infrastructures throughout wireless communication and networking technologies. With a help to the development of sensors and their communications, the healthcare systems have provided great convenience and feasibility to patients and even ordinary people who like to monitor their fitness condition for their healthy lives. However, WBAN has several significant differences from general wireless sensor networks such as higher path loss, concerns about data transmission over bio-effect, less node density, smaller system scale, slower rate signals, etc [30, 34-35].

Due to the limitation of the size in the sensor nodes on human body, power consumption is the one of the biggest issues in WBAN. Since human body consists of comparatively higher path loss rather than the one in normal air interface, power related problems in WBAN can be more serious than any other wireless network systems.

Furthermore, uneasy battery replacement on human body is another concern related to energy consumption problems [41-43].

The signals in WBAN are vital ones for unsupervised, continuous, and ambulatory monitoring so that it can significantly reduce the number of staffs in a hospital. Thus, the reliability is a critical problem in WBAN since it is occasionally delivers critical or emergence signals for intensive care patients. It is noticeable that reliable communications result in energy-efficient system since it can reduce the possibilities of error recovery or retransmission processes [40].

However, it is a nontrivial task to guarantee that the system design optimizes both energy efficiency and reliability simultaneously. For reliable communications, redundant data transmission cannot be avoided, and it usually results in more energy consumption. Related works shows us energy efficiency or reliability has been acquired utilizing multi-hop communications, utilization of relay nodes, and a combination of both. Also, researches on various MAC approaches have been done to pursuit desirable reliability, but it has never been easy to achieve two different design requirements simultaneously.

1. 2. Problem Statement

In wireless sensor networks, limited resources have been remarkable issues due to the size limitation of sensors. It is more significant in wireless body area networks since the sensors are supposed to be on a human body. The size limitation in WBAN directly associates with the energy-efficiency problems that are the biggest issues in WBAN.

In addition, reliable data communication is required since the data of healthcare systems can be critical patients' information. The information can be unsupervised, continuous, or ambulatory health monitoring. Since it is also noticeable that packet transmission failure affects transmission delay, the reliability of the desired system is required.

1. 3. Contributions

First, we investigate legacy optimal routing solution which uses flow-level routing mechanisms [24], and derive an innovative analytical model which considers rapidly changing cross-traffic conditions. We then show that the optimal solution can be found for a given set of system requirements. Otherwise, we should look for its alternative as suboptimal. We also propose practical schemes that can be implemented without significant performance deviation from the optimal solution. Using the best of the schemes which were developed so far, we construct a load-balancing aware feedback control system to approximate the optimal solution's behavior. Finally, we elaborate on several simulations to verify that the proposed scheme is practically implementable.

Also, we investigate the conventional routing scheme and derive an innovative analytical model which considers linear network coding design approach in WBAN. We verify the system design utilizing different acknowledgment technologies over MAC layer. We also parameterize the analytical models in terms of two main design factors such as energy-efficiency and reliability. Finally, we elaborate on several simulations to verify that the proposed scheme is energy-efficient and reliable at the same time.

1. 4. Dissertation Outline

Chapter 1 has provided an overview of wireless sensor networks and this dissertation's introduction. In Chapter 2, the study in a novel dynamic load-balancing aware routing algorithm is given for multi-path wireless sensor networks. Chapter 3 presents work on an application of linear network coding (LNC) over wireless body area network. And, this is followed by related works in Chapter 4. Finally, Chapter 5 summarizes and concludes with future research directions.

CHAPTER 2

Dynamic Load-Balancing in Wireless Sensor Networks

2. 1. Motivations

Recently, a class of robust routing algorithms, termed *multipath routing*, has been proposed as a means to efficiently distribute and control the overall traffic across multiple paths. Such algorithms can monitor the variation in traffic flow and instant node capacity, adjust them jointly, and thus enhance network performance [14-18]. Load balancing overcomes the capacity limitation of single path networking by distributing incoming data traffic onto multiple paths, and reduces congestion by routing traffic through less-congested paths. Hence, it leads to decrease the use of unreliable wireless links, diminish the end-to-end delay, and perform load-balancing [18-23].

It is a nontrivial task to guarantee that a dominant path always remains optimal for long time duration, because traffic conditions are rapidly changing in real time. Network traffic conditions vary rapidly and often impossible to estimate due to uncontrollable parameters such as cross-traffic, bursty packets, node mobility, etc. In addition, the reconfiguration of existing paths based on measurements and conventional feedback methodology may be rendered obsolete ahead of it use. What is needed is a real-time load-balancing routing algorithm that can forecast future traffic flow and provide effective control mechanisms using current flow status.

2. 2. System Model

We consider a network model with multiple paths in Figure1. Suppose that we have a simple multi-path network with single source and single destination, and in between there are N different multiple paths where the data from the source choose to find its destination where x_i is the flow (generally, in data bits/sec) of the i^{th} path, and C_i is the capacity of the i^{th} path as shown in Figure 1. Also, there is cross-traffic source, f_i, for the input of each queue i, which cannot be controlled by this system. D. Bertsekas and R. Gallager [24] defined a legacy optimal routing solution using flow-level analysis. However, they did not consider the unknown parameter, cross-traffic source but it is a significant design factor. In addition, the flow-level approach was shown less complicated and more appropriate rather than the packet level in [25].

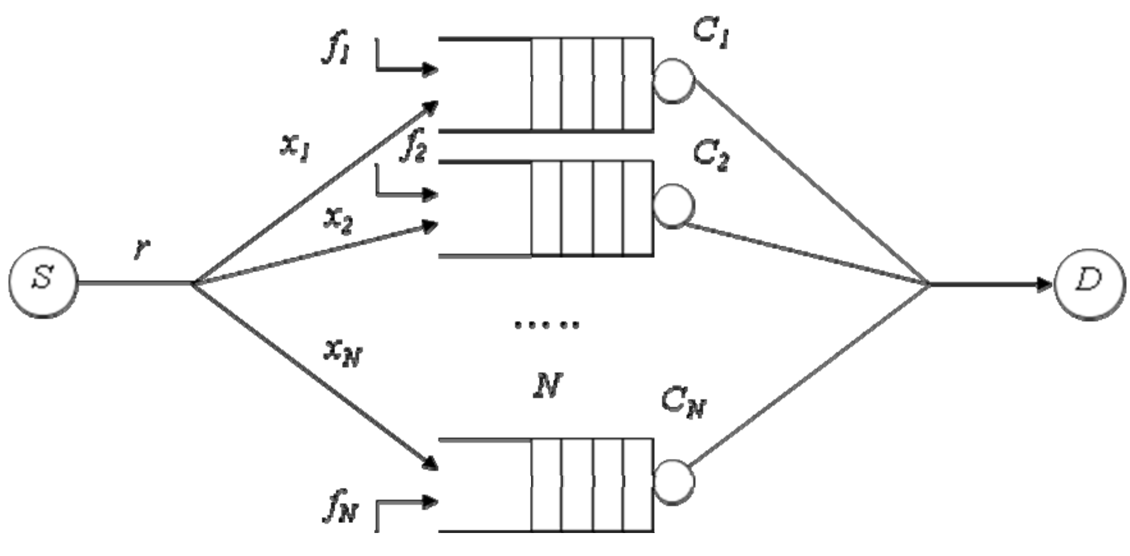


Figure 1 Block diagram of a multi-path network

2. 3. Analytical Model

2.3.1. Optimal Routing – General Approach

We can derive the initial objective function of total delay with respect to total flow in (1) in order to achieve the minimum mean system delay, D_T.

$$\text{Min } D_T(x_1, x_2, ..., x_N) = \frac{1}{r}\sum_{i=1}^{N} D_i(x_i) \tag{1}$$

$$\text{Subject to } r = \sum_{i=1}^{N} x_i$$

To solve the given linear optimization problem (1), we derive the parameters related to the delay factors based on the characteristics of each queue. When μ_i is the processing rate, and x_i is arrival rate for given *M/M/1* queue,

$$D_i(x_i) = \frac{x_i}{\mu_i - (f_i + x_i)}, \tag{2}$$

where $D_i(x_i)$ is traffic flow on the i^{th} path. This can be utilized to optimize the objective function. We apply the Lagrangian Multiplication approach as follows:

$$L(x_1, ..., x_N, \lambda) = D_T(x_1, ..., x_N) + \lambda(r - \sum_{i=1}^{N} x_i) \tag{3}$$

To simplify the calculation procedure, let us suppose that we have two link cases, which is "i = 2." Then, we obtain two cases as follows:

1. When x^*_1 = r, and x^*_2 = 0,

$$r \le (\mu_1 - f_1) - \sqrt{(\mu_1 - f_1)(\mu_2 - f_2)} \tag{4}$$

2. When $x^*_1 > 0$, and $x^*_2 > 0$, we have two equal values for x^*_1 and x^*_2.

$$\frac{\mu_1 - f_1}{(\mu_1 - (f_1 + x_1^*))^2} = \frac{\mu_2 - f_2}{(\mu_2 - (f_2 + x_2^*))^2} \tag{5}$$

The case 2 is obviously of our interest in this paper.

$$x_1^* = \frac{\sqrt{q_1}[r + \sqrt{q_1}\sqrt{q_2} - q_2]}{\sqrt{q_1} + \sqrt{q_2}},\ x_2^* = \frac{\sqrt{q_2}[r + \sqrt{q_1}\sqrt{q_2} - q_1]}{\sqrt{q_1} + \sqrt{q_2}}, \tag{6}$$

where $q_i = \mu_i - f_i,\ i = 1, 2.$

Hence using x^*_1 and x^*_2, the cost function which is the mean system delay can be derived as follows:

$$D_T = \frac{1}{r}[D_1(x_1^*) + D_2(x_2^*)] = \frac{2r - (\sqrt{q_1} - \sqrt{q_2})^2}{r(q_1 + q_2 - r)} \quad (7)$$

2.3.2. Simplification

The equation above can be too complicated to process in the mobile nodes of wireless sensor networks of which challenge is power-efficiency and limited resource. [26] shows different approaches, as well as intuitive and heuristic methods. However, in this paper, the equation is simplified to achieve a practical design which can be more feasible. Hence we introduce a load-balancing mechanism that is helpful to achieve equally distributed end-to-end delay for the i^{th} path. First, we solve a simple problem with no cross-traffic for simplicity.

The delay for the i^{th} path is as follows:

$$d_i(x_i) = \frac{1}{\mu_i - x_i} = \frac{1}{\mu_i - r\alpha_i}, \quad (8)$$

where $x_i = \alpha_i r,\ 0 \le \alpha_i \le 1$

α_i is the load-balancing parameter for the i^{th} path. To get equally load-balanced, the delay function of every path should have the identical value.

$$d_i^* = \frac{1}{\mu_1 - r\alpha_1} = \frac{1}{\mu_2 - r\alpha_2} = ... = \frac{1}{\mu_N - r\alpha_N} \quad (9)$$

After calculations, we obtain a solution for d_i^* as follows:

$$d_i^* = \frac{N}{(\sum_{i=1}^{N} \mu_i - r)} = \frac{1}{\mu_i - r\alpha_i}, \text{ for all } i \in 1,2,...,N \quad (10)$$

We revisit the original problem by introducing the cross-traffic factor f_i, and consider a simple case ($i=2$) as follows:

$$d_i^* = \frac{1}{\mu_i - (x_i + f_i)} = \frac{1}{q_i - x_i} \tag{11}$$

$$\alpha_1 = \frac{q_1 - q_2 + r}{2r},\ \alpha_2 = \frac{q_2 - q_1 + r}{2r} \tag{12}$$

$$x_1 = \frac{q_1 - q_2 + r}{2},\ x_2 = \frac{q_2 - q_1 + r}{2} \tag{13}$$

Hence we come up with significantly simplified results rather than the original one as follows:

$$D_{T(UD-scheme)} = \frac{1}{r}[D_1(x_1) + D_2(x_2)] = \frac{2}{q_2 + q_1 - r} \tag{14}$$

2.3.3. Analysis

It is important to analyze the simplified version of approach to verify that it can still maintain the performance level of the original solution. Let us suppose the original scheme is called as the Opt-scheme and the uniform delay scheme as the UD-scheme for simplicity. First, let us rewrite the equation for the Opt-scheme so that we can easily analyze it and compare with the UD-scheme.

$$\begin{aligned} D_{T(Opt-scheme,No\_CT)} &= \frac{2r - (\sqrt{\mu_1} - \sqrt{\mu_2})^2}{r(\mu_1 + \mu_2 - r)} \\ &= -\frac{(\sqrt{\mu_1} - \sqrt{\mu_2})^2}{r(\mu_1 + \mu_2)} + \frac{(\sqrt{\mu_1} + \sqrt{\mu_2})^2}{(\mu_1 + \mu_2)(\mu_1 + \mu_2 - r)} \end{aligned} \tag{15}$$

(15) is the mean system delay of the Opt-scheme with no cross traffic source, and is rewritten as the sum of two fractional equations. When $r = \frac{(\sqrt{\mu_1} - \sqrt{\mu_2})^2}{2}$, D_T becomes

zero and there is no meaning when r is equal or less than this value since we only consider for $\frac{(\sqrt{\mu_1}-\sqrt{\mu_2})^2}{2} < r < \mu_1 + \mu_2$.

For the proper region above, the second fractional equation dominates to be positive value. Hence the second equation is always equal to or greater than the $D_{T(UD\text{-}scheme)}$, (14). They can be equal when $\mu_1 = \mu_2$. When the difference between μ_1, μ_2 gets bigger, the second equation gets smaller and close to $\frac{D_{T(Opt\text{-}scheme)}}{2}$.

The effect of the first fractional equation gets smaller when r is close to the maximum value.

2.3.4. Extreme Case

We verify the solution by applying special scenarios where cross traffic sources act extremely and figure out how we can work around if we can.

General Case:

For general case with usual node conditions, the capacities of each queue, μ_1, μ_2, can be assumed equal numbers. (when $\mu_1 = \mu_2$) And, their cross-traffic inputs, which are the dynamic factors, are equally distributed for a normal condition. ($f_1 = f_2 \Leftrightarrow q_1 = q_2$, since $\mu_1 = \mu_2$) With this general case, we can simply use the UD-scheme results.

Extreme Case: Burst Case

Let us consider that the capacities of both queues are equal as the general case above (when $\mu_1 = \mu_2$). For the extreme case, the cross traffic of the queue #1's input, f_1, is equal to zero, and the cross traffic of the queue #2's input, f_2, is equal to the maximum value, μ_1.

In addition, it works similarly with the opposite case.

$$f_{1\_Extreme} = 0, f_{2\_Extreme} = \mu_2 = \mu_1,$$

$$\text{since } 0 \le f_1 \le \mu_1 \text{ and } 0 \le f_2 \le \mu_2,$$

$$q_1 = \mu_1,\ q_2 = 0$$

Hence the Opt-scheme equation becomes:

$$D_{T(Opt-scheme,CT,q_1=\mu_1,q_2=0)} = -\frac{1}{r} + \frac{1}{\mu_1 - r} \tag{16}$$

Thus we can apply the simplified equation for general case, while we can apply the above results with the Opt-scheme for the extreme cases.

2. 4. Implementation

2.4.1. Concepts: Architecture Design

Based on the derived analytical modeling, the design tries to equalize the delay for each path, *i* to get the system mean delay minimized from the given source to the given destination, which is the “S-D pair.” The system tries to track the end-to-end delay for each path, and the real time judgment of the input traffic distribution to intermediate nodes can be made based on the end-to-end delay data in order to control the load-balancing parameter in Fig. 1 (when $i = 2$). This feedback control system approximates the optimal solution’s behavior and implements its feasible system as shown in Figure 2.

The Delay Measurement System measures the delays for the i^{th} path, within a specific time window, and outputs, Delay[k]. Load Balancer adjusts the load-balancing factor to make the path delays uniform, and outputs the load-balancing factor, $\Delta\alpha_i[k]$.

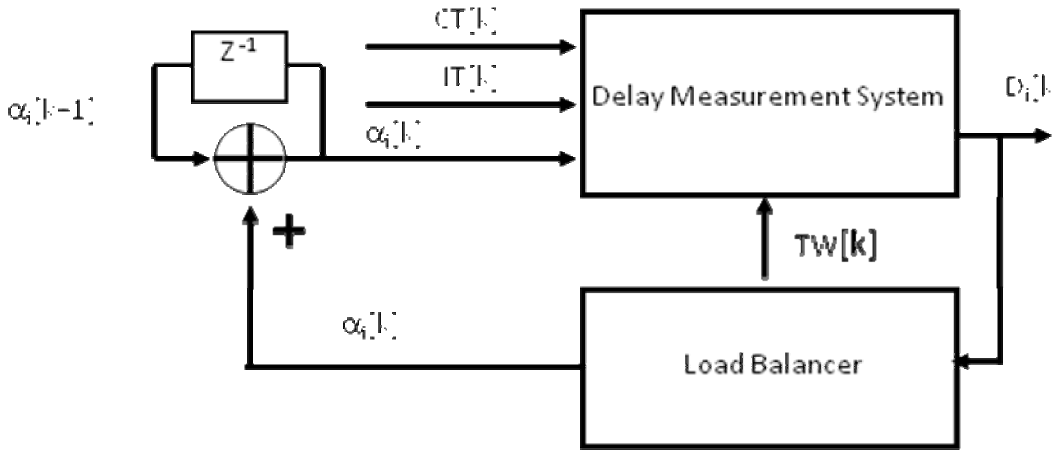


Figure 2 Block diagram of dynamic load-balancing aware feedback control system

In addition, the design parameters are as follows:

- IT[k]: input traffic sources coming in the source for the S-D pair at the discrete time of *k*.
- CT[k]: cross traffic sources coming in the intermediate nodes on the path, *i*, for the S-D pair at the discrete time of *k*.
- D_i[k]: delay output from the system for the i^{th} path,, in the S-D pair at the discrete time of *k*.
- $\alpha_i[k]$: load-balancing factor for the input of the i^{th} path, at the discrete time of k. ($0 \leq \alpha_i[k] \leq 1$)
- $\Delta\alpha_i[k]$: adjustment factor for the load-balancing factor, α_i[k]. ($-1 \leq \Delta\alpha_i[k] \leq 1$)
- *TW[k]*: time window size for the delay measurement at k. This value can be fixed or variable in time.

2.4.2. Algorithm Design

Implementation environments are as follows:

- No limitation on queue sizes
- Test packet generation interval: multiple times of the delay time window, i*TW (i = 1, 2, 3, etc.)
- Queue processing priority: test packets are always prior to data packet.

Initialization:

- $\alpha_i[0] = 1/N$, (N = total number of paths for S-D pair)
- $\Delta\alpha_i[0] = 0$, $D_i[k] = 0$
- W[k]: varies depending on user defined input.

Calculation Factors:

- $D_{T\_D}[k]$ (Total System Delay): total delay time over entire paths in the S-D pair.
- $D_{T\_MSD}[k]$: Mean System Delay per a packet

$$D_{T\_MSD}[k] = \frac{\sum_{i=1}^{N} D_i[k]}{n\_P[k]} \tag{17}$$

- n_P[k]: the number of packet received at the destination at the discrete time of *k*.

2. 5. Simulation Results

The simulation environments are as follows:

- Simple four node networks including fixed source and destination nodes. (as shown in Figure 1 when $i = 2$)
- S-D nodes have instant processing time.
- Queues #1 and #2 have fixed service time to 0.1 sec.
- $\mu_1 = \mu_2$ =10 packet/sec for the Queue #1 and #2
- Queues #1 and #2 have infinite buffer sizes.

The Distributions of input and cross traffics are as follows:

- Input streams: Poisson arrival with a rate, r
- Cross-traffic streams: Poisson arrival with rates, f_1 (for Queue #1), f_2 (for Queue #1). $x_1 + f_1 < \mu_1$, $x_2 + f_2 < \mu_2$

As shown in Figure 3, 4, 5, the proposed scheme as a whole outperforms that without load-balancing mechanism in terms of offered load, mean system delay, and overall end-to-end delay. Also, the time window size significantly determines the characteristics of the feedback control system such as promptness, stability, etc. Thus it can be variously applied according to the system's traffic characteristics such as the burstiness, traffic load statistics, etc.

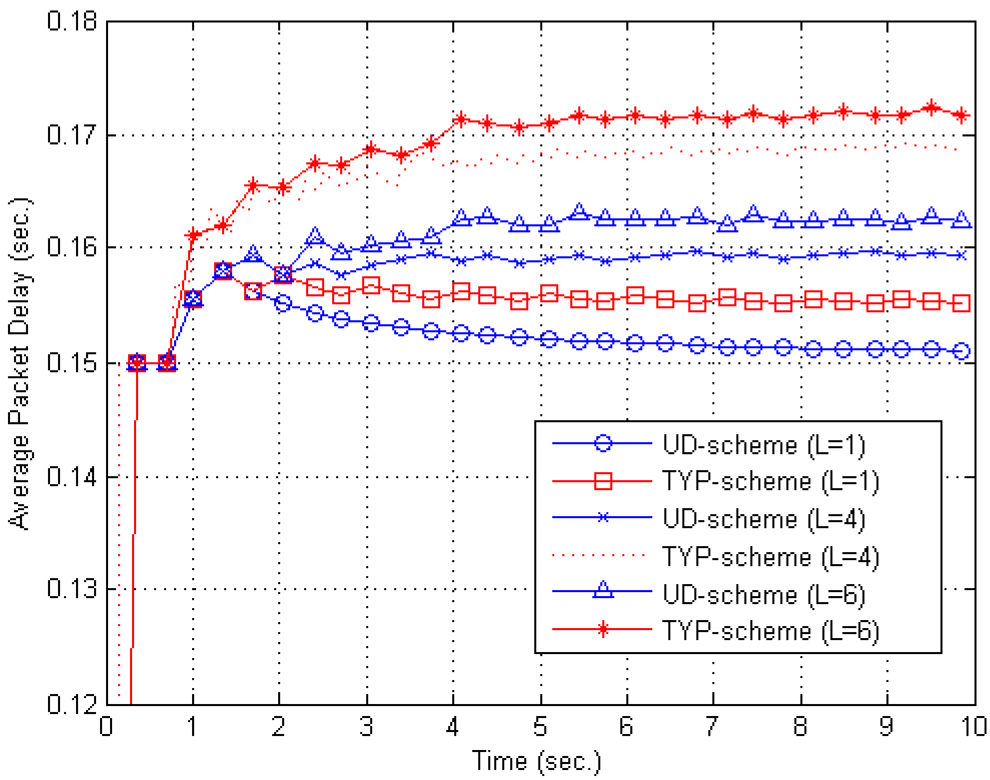


Figure 3 Mean system delay with varying the Lamda values of cross-traffic sources

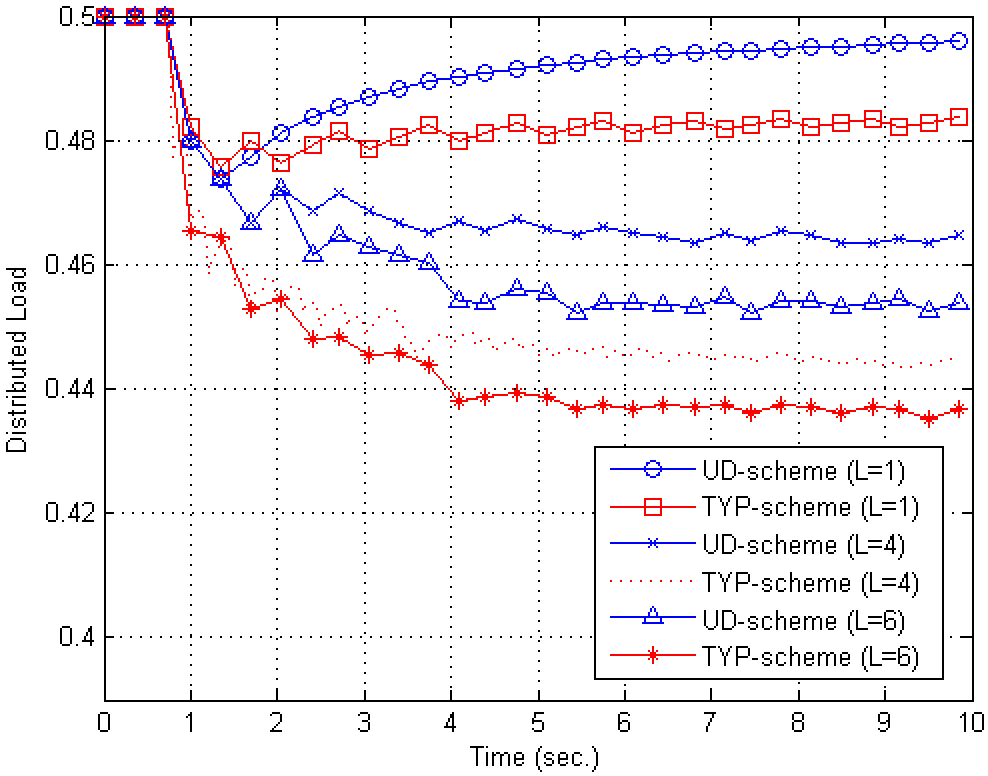


Figure 4 Distributed load with varying the Lamda values of cross-traffic sources.

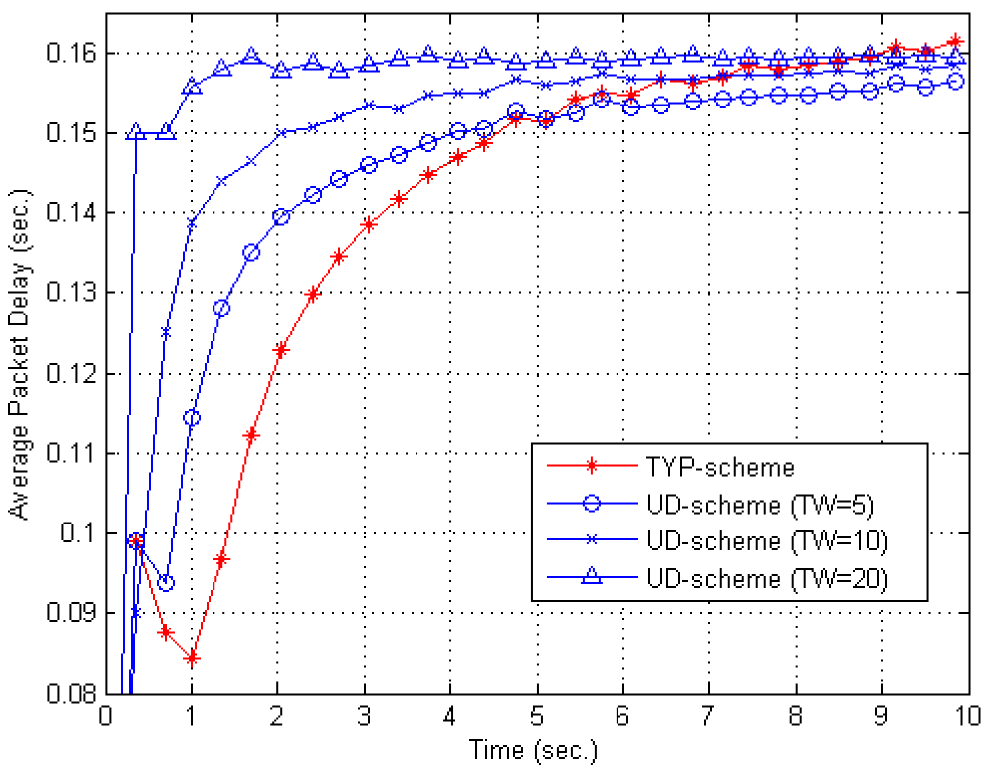


Figure 5 Mean system delay with varying the time window size of the design

2. 6. Remarks

In this Chapter, we proposed an innovative multipath routing network design scheme utilizing dynamic load-balancing aware feedback control system which can predict future traffic flow with preloaded traffic control. In this system, we emphasized end-to-end delay, which is only used for a design parameter, as a means for coping with limited resources on sensor platforms. In addition, we implemented a practical model under the desired constraints based on the derived analytical model, and verified that the proposed scheme can enhance network performance in terms of balanced load, mean system delay, and overall end-to-end delay.

CHAPTER 3

Linear Network Coding Application in WBAN

3. 1. Wireless Body Area Networks

Recently research interests and demands on healthcare related applications have been growing rapidly since the rate of growth in population of aged people is significantly steep and adult disease has become more general and spread to younger people. In addition, people's concerns about their health, fitness as well-being life have become more and more as healthcare related products and applications have obtained great attention. Therefore, remote monitoring and automatic measurement via wireless body area networks can reduce medical measurement errors and workload, while it can increase efficiency of hospital staff members, and improve the patients' comfort.

However, today's technologies of wireless body area networks are still facing with problems and challenges that must be overcome. The standardization of IEEE 802.15.6 is still in progress and not complete, yet. In addition, the sensors on or along human body are not truly wireless, yet since there are multi-lead sensors such as ECG, EEG, EMG, etc. that are connected by wires. The recent MAC technology mostly used for WBAN is Time Driven Multiple Access (TDMA) since it is good for maximum bandwidth utilization and low power consumption. However, it has several weak points such as difficulty in synchronization and high effect of packet failure that can be resolved by various kinds of research works in this area [30-34].

Although WBAN is a kind of wireless sensor networks, they have some significant differences so special design strategies should be considered for their own characteristics. The comparisons between wireless sensor networks and wireless body area networks are shown in Table 1 below. And, type of signals and parameters are shown in Table 2.

Table 1 Comparisons between WBAN and WSN

Items	WBAN	WSN
Size of sensors	Smaller	Small
Deployment	More strategic	Redundancy allowed
Density	Not node-dense	Dense
Data rate	Stable or periodic	Commonly event-based
Latency	Real-time processing	Not critical
Mobility	Can be mobile	Stable
Path loss	Higher	Normal
Concerns about bio-effect	Yes	No
System scale	Smaller	Normal

Table 2 Type of signals and sensing parameters

Signal Type	Signal Name	Description	Data Rate
Physiological signals	ECG	Heart's electrical activity	High
	EEG	Brain's electrical activity	High
	EMG	Muscle's electrical activity	Very high
	Blood pressure	Systolic and diastolic human blood pressure	Low
	Pulse oxymetry	Saturation level of oxygen in the blood	Very low
	CO2 gas	Gaseous carbon dioxide level	Very low
	Blood glucose	Blood sugar. Amount of glucose circulating in the blood	High
Environmental signals	Temperature	Human body temperature	Very low
	Humidity	Humidity of the immediate environment around a person	Very low
	Light	Brightness of the immediate environment around a person	Very low
Motion signals	Accelerometer	Recognition and monitoring of body posture and	High
	Gyroscope	Measuring or maintaining orientation	High
	Location	Location of the human body	High

(Very high: ~ 6.4 kbps, High: ~ 1 kbps, Low: ~ 200 bps, Very low: ~ 20 bps)

3. 2. System Model

We consider a network model with multiple sources and a relay in Figure 6. Suppose that we have a simple multi-hop relay network with multiple sources and a single destination. In Figure 6, the source node 1, S1, tries to send the data A, and the source node 2, S2, tries to send the data B. And, the relay node, R1, combines data and relays the data to the destination node, T.

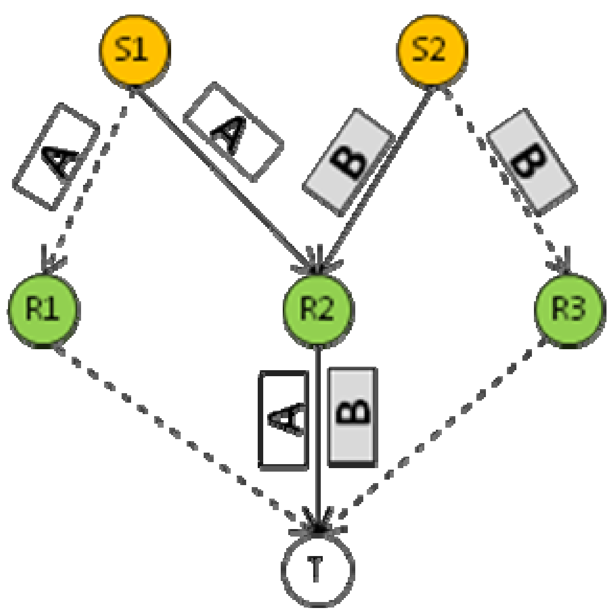


Figure 6 Network system model

3.2.1. Linear Network Coding (LNC)

Linear Network Coding (LNC) is a network coding scheme where all functions are linear combination of incoming messages. The output flow at a given node is obtained as a linear combination of its input flows. The coefficients of the combination are defined as selections from a finite field. Therefore, the linearly combined data can be solvable over multicast network in a sufficiently large field, only if the coefficient matrix keeps linearly independent. [44-50] The LNC applied network diagram is shown in Figure 7, and LNC functional diagram is shown in Figure 8.

LNC is good for WBAN since it can provide robustness, low-delay, and improve throughput over multi-hop relay WBAN. Benefits of using LNC in WBAN are high reliability, high throughput, low delay, and comparatively independent from the topology design.

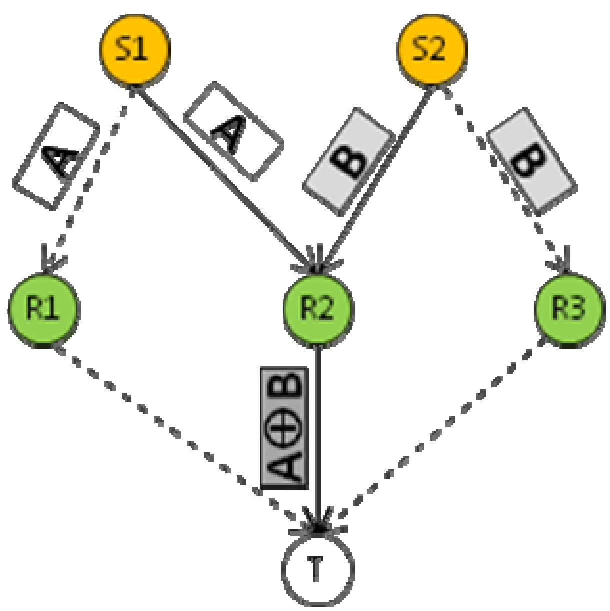


Figure 7 LNC applied network diagram

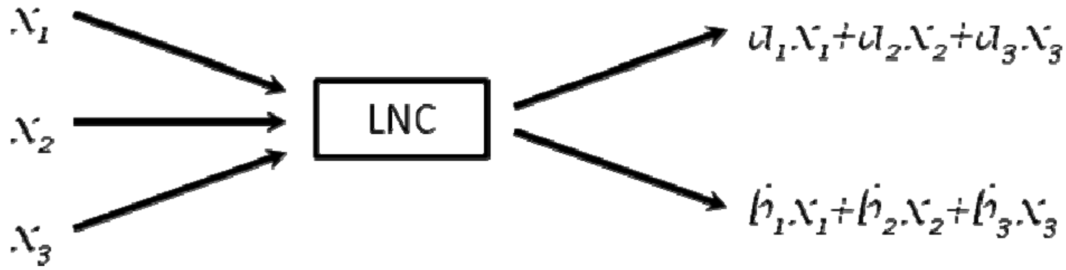


Figure 8 Linear network coding functional diagram

3.2.2. Retransmission Process

A routing scheme determines how its retransmission flow efficiently works. Retransmission process initiates when the receiver node receives the transmitted data from the source incorrectly, and it requests for the data recovery via retransmission of the data. The conventional routing scheme should retransmit all the data from the sources to the receiver node in the opposite direction of the data transmission. However, the LNC scheme just retransmit the data from the relay node which is capable of linearly network coding. It can significantly reduce the cycles of retransmission process and more efficient.

The proposed LNC scheme is a sequential LNC scheme which holds the data for a unit time frame, and linearly combines the incoming data from all sources with the given linearly independent coefficient vectors. After then, it outputs the combined data in the next unit time frame. Those LNC applied data transmission process is described in Figure 9 in a time domain.

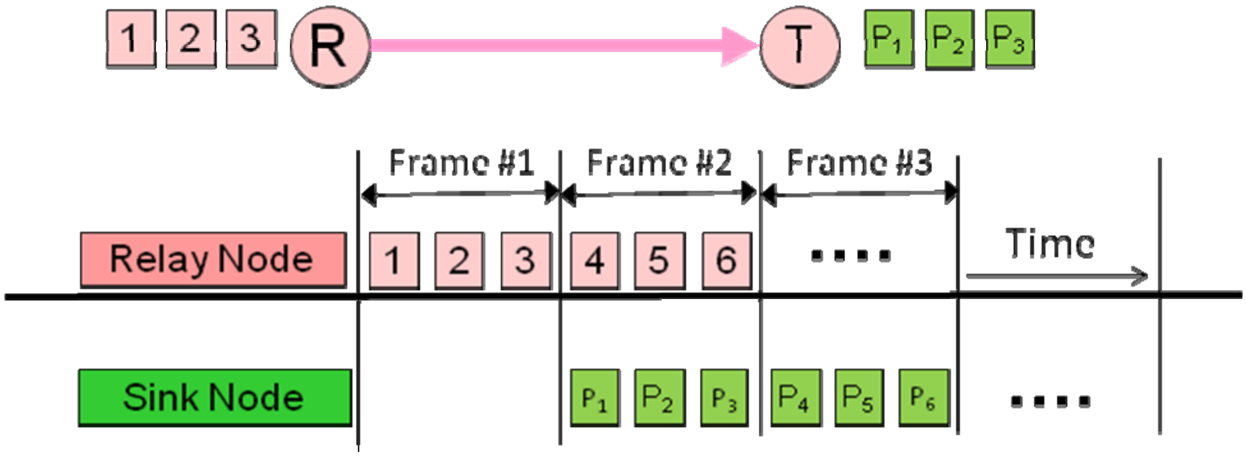


Figure 9 LNC applied data transmission in a time domain

3. 3. Analytical Model

We consider a network model with two paths in Figure 2. Suppose that we have a simple two path network with a single source and single destination. To ensure the data transmission, the source node, S, transmits the data using two different paths for the reliability. Let's suppose that p is the probability of transmission on a link. Also, the data is supposed to be transmitted and received between S and D nodes shown in Figure 10. And, each transmission is supposed to have a *p* probability of a success. For the simplest case, let's suppose that if we have a message can be transmitted once correctly with an allowance of m trials of retransmissions, it can be treated as a successful transmission. The probability of success (n=1) can be expressed below:

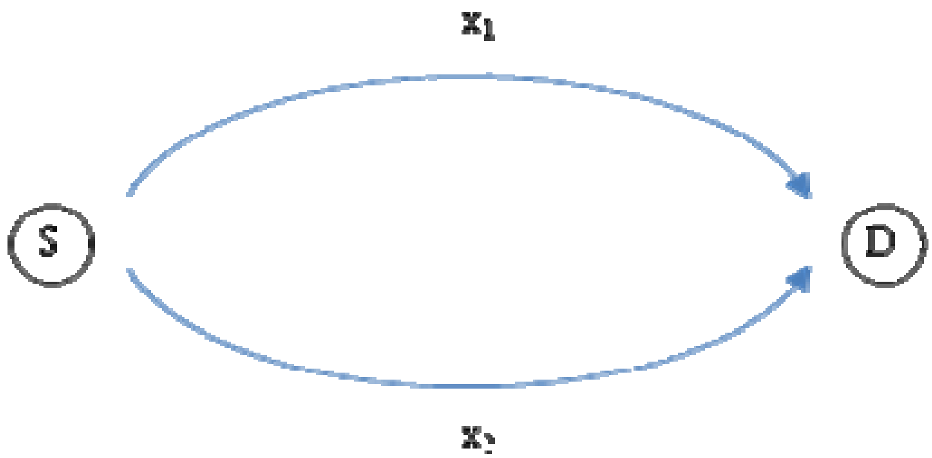


Figure 10 Simple Network Diagram

$$\Pr(Success, n=1) = p + (1-p)p + ... + (1-p)^{m-1} p \tag{18}$$

$$= p\{1 + (1-p) + ... + (1-p)^{m-1}\}$$

$$= 1 - (1-p)^m$$

Also, for further complicated case, data is only delivered correctly only if the data was received correctly in n times.

$$\Pr_{Max}(Success, n) = (1-(1-p)^m)^n \tag{19}$$

To increase the probability of transmission, we utilize a linear network coding scheme. And, here is our proposed scheme with linearly network coding.

$$\Pr_{LNC}(Success) = \sum_{x=0}^{L-n} H_{n,x} p^n (1-p)^x \tag{20}$$

where $where\ H_{n,x} = \dfrac{(n-1+x)!}{(n-1)!x!}$

Suppose we have n is equal to 1, then

$$\Pr_{LNC}(Success, n=1) = \sum_{x=0}^{m} p(1-p)^x = 1-(1-p)^m$$

$$= \Pr_{Max}(Success, n=1) \qquad (21)$$

n is the total sequence number, and m is the maximum number of retransmissions. L is the m times n.

Suppose that wireless body area network consists of multiple sources, relays and a sink. Each source has limited time slot (TS). All sources have equivalent transmission opportunities. A sink requires every data from all sources. There are two different MAC protocols such as “Non-ACK” and “ACK.” In “Non-ACK,” the receiver node does not send the acknowledgment signal to notify whether the previous reception is correct or not. Thus, this scheme requires the maximum number of retransmission trials for each packet transmission. However, in “ACK” the receiver node sends the acknowledgment signal to notify that the previous reception is correct so that the sender does not need to retransmit the data and can make the data transmission more efficient than “Non-ACK.” We select the “ACK” MAC protocol as a design scheme since it can produce more challenges to research than “Non-ACK.” Relay nodes are capable of linear network coding.

The parameters are shown as below:

- m = Maximum number of transmission per time slot
- n = Number of sources per frame
- L = Maximum number of transmission per frame (= m·n)
- p = Probability of successful transmission
- PRR = Packet Reception Ratio per frame
- E(TX) = Average number of transmissions per frame
- E(ETX) = Average number of effective transmissions per frame

There are two important factors which we consider, which are PRR, Packet Reception

Ratio, and Average Number of Transmissions. We utilize the two factors to verify how the proposed design scheme performs over the conventional design scheme.

3.3.1. Packet Reception Ratio

PRR is the packet reception ratio per frame that shows the ratio of successful transmission with allowance of m retransmissions per each source with n sources per frame. To be a successful transmission, it should receive n source data correctly per frame.

The PRR for the scheme which Linear Network Coding is not applied to is as below:

$$PRR_{No\_LNC} = (1-(1-p)^m)^n \tag{22}$$

However, the PRR with LNC scheme is shown as below:

$$PRR_{LNC} = \sum_{x=n}^{L} {}_L C_x p^x (1-p)^{L-x} \tag{23}$$

3.3.2. Average Number of Transmissions

Also, the average number of transmissions for the scheme without LNC is shown as below:

$$E(TX_{No\_LNC}) = \frac{1-(1-p)^{m-1}}{p} + (1-p)^{m-1} \tag{24}$$

The average number of transmission with LNC scheme is shown as below:

$$E(TX_{LNC}) = \sum_{x=n}^{L-n} (n+x) H_{n,x} p^n (1-p)^x, \tag{25}$$

$$where\ H_{n,x} = \frac{(n-1+x)!}{(n-1)!x!}$$

3. 4. Results

3.4.1. Packet Reception Ratio

First, we vary the n value with the fixed m value to examine the packet reception ratio with the LNC applied scheme and the conventional routing scheme as shown in Figure 11-13. Also, as a reference, we plot the PRR for n = 1, which is equivalently primitive case for both schemes. With fixed m, as n is bigger, the conventional routing scheme get worse, while the LNC scheme works better with bigger n than the conventional one. For all cases, the LNC applied scheme always outperforms the conventional routing one.

For better understanding the comparisons of PRR for both schemes, we plot the differences between them as shown in Figure 14-15. We can easily recognize how the LNC scheme outperforms the one without LNC from those graphs. In Figure 14, we observe that as n is larger, much better performance from LNC takes place near the mean value that is within 0.4 ~ 0.5, here with more retransmission opportunities. On the other hand, with more m values, more maximum number of retransmissions, the graph shifts to the left, which means that the outperformance of the LNC scheme takes place at less possibility of success for a link as shown in Figure 15.

You should notice that the meaningful zone for the p value, success rate for a link, is within 0.3 ~ 0.7. Therefore, the results are very valuable for those areas of the p value.

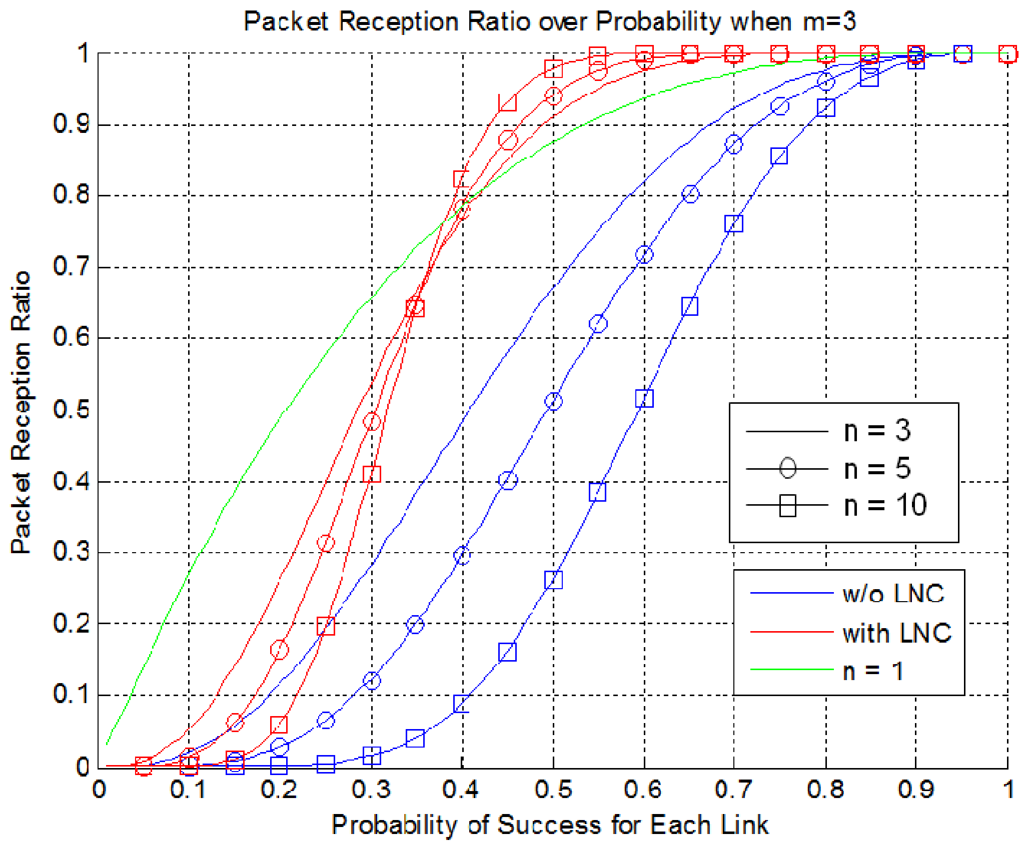


Figure 11 Packet reception ratio when m = 3

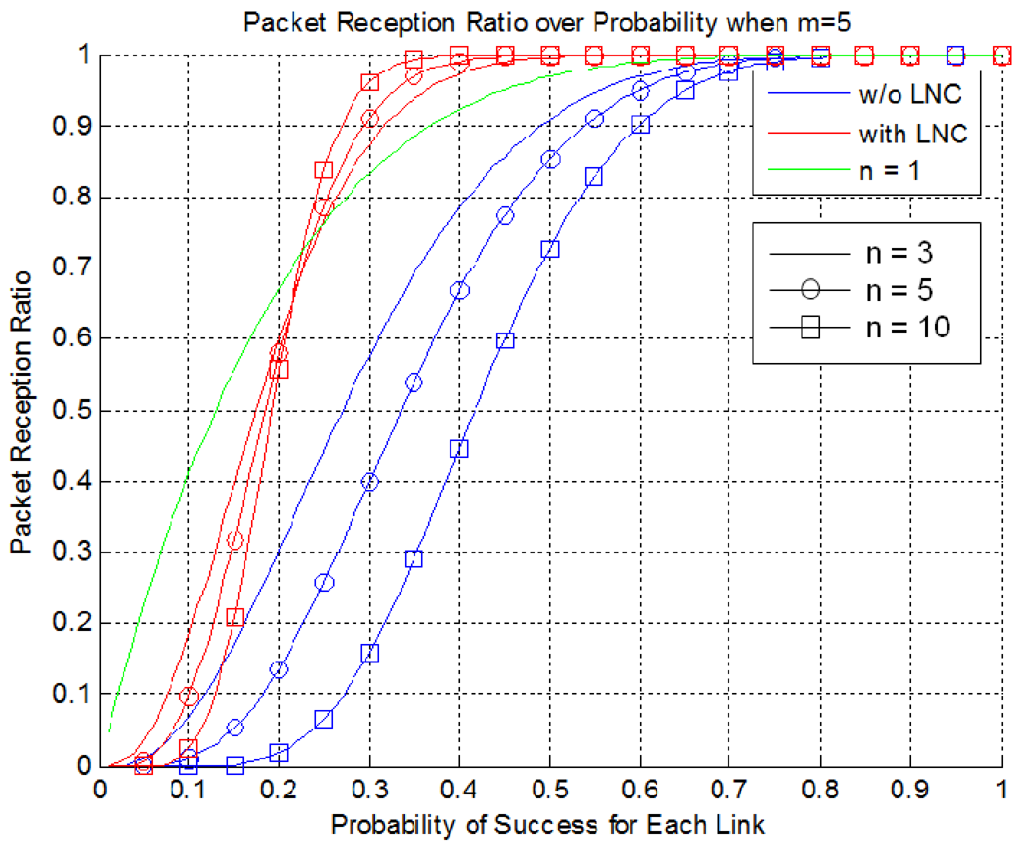


Figure 12 Packet reception ratio when m = 5

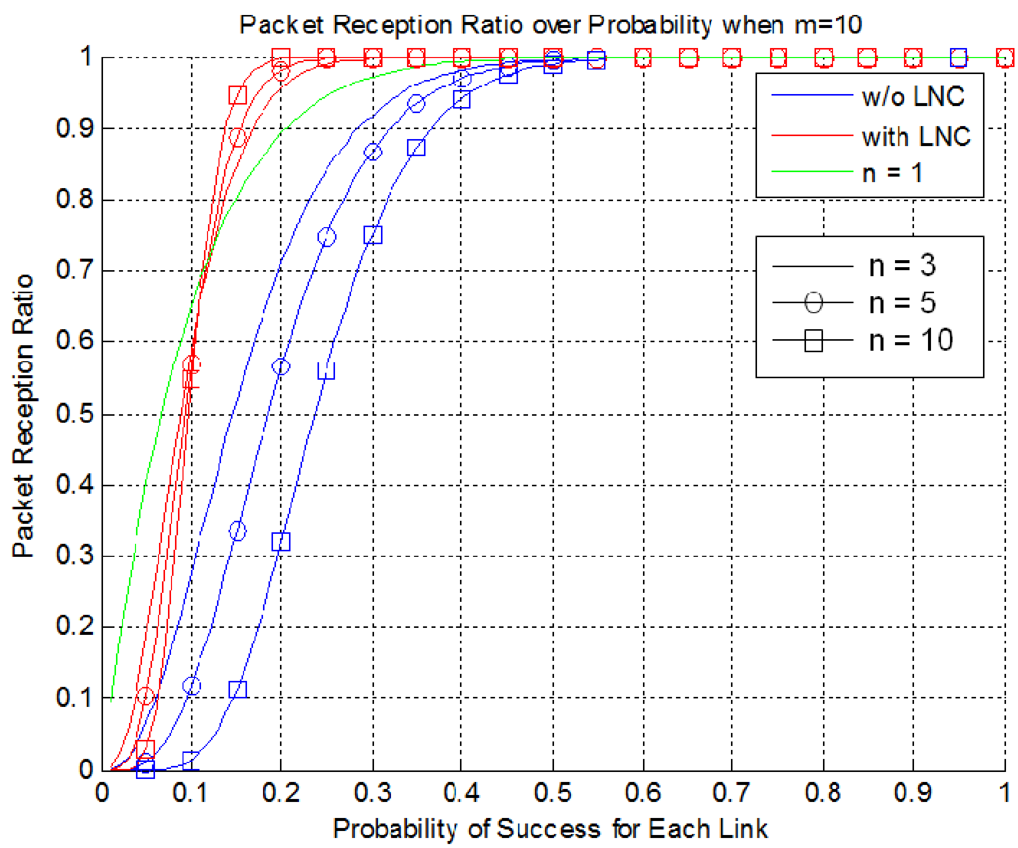


Figure 13 Packet reception ratio when m = 10

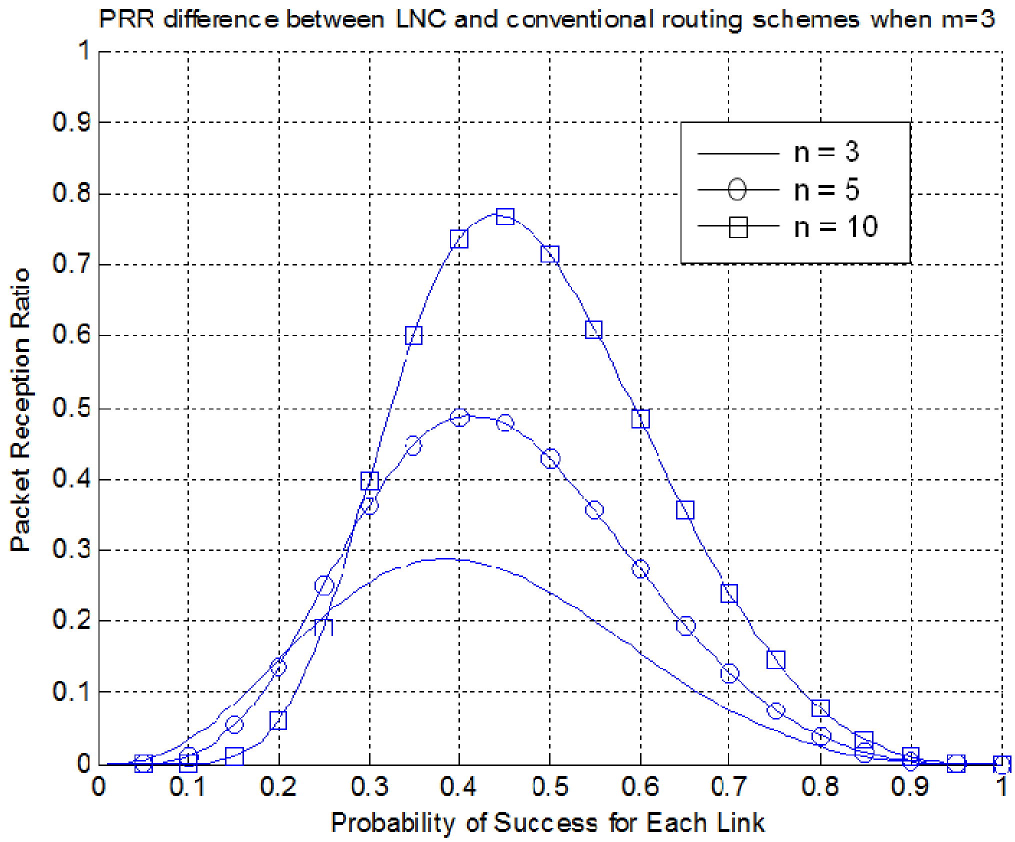


Figure 14 PRR differences between the LNC and conventional routing scheme with fixed value of m

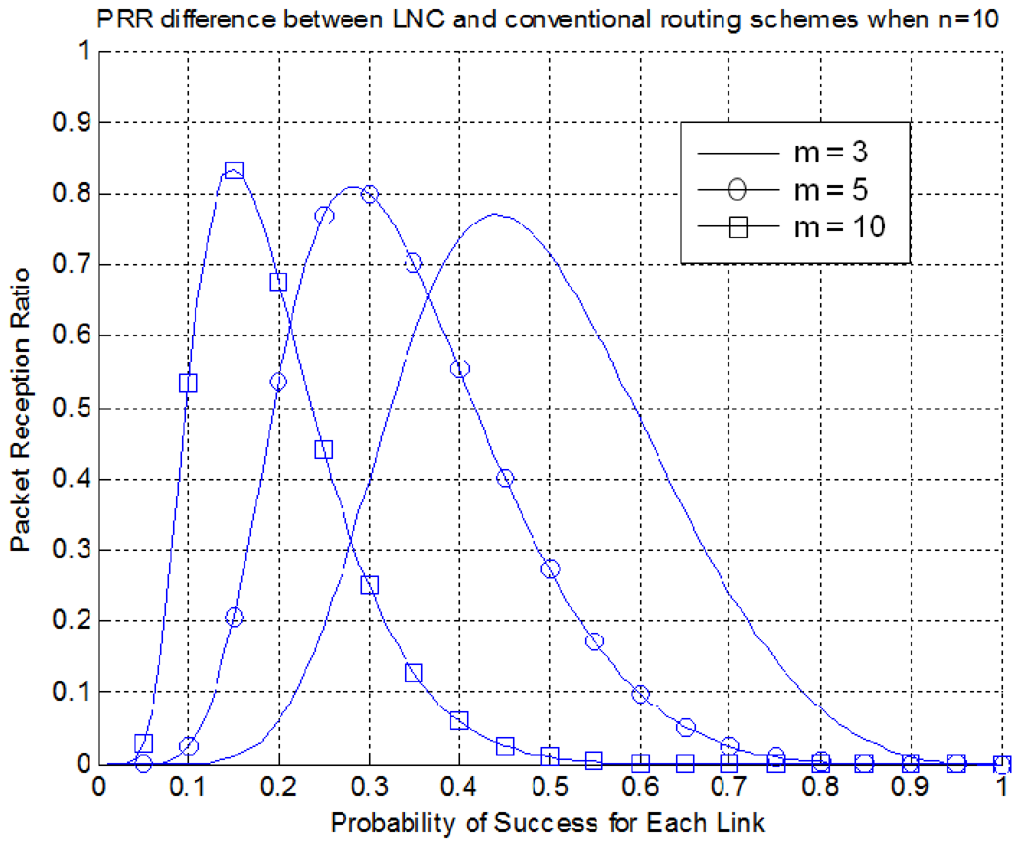


Figure 15 PRR differences between the LNC and conventional routing scheme with fixed value of n

3.4.2. Average number of transmissions

As shown in Figure 16-18, the LNC scheme requires more average number of transmissions than the one without LNC. It needs more redundant packets to be transmitted with more number of sources. However, the number of redundant packets produced by the LNC scheme is not much costly at most up to 20 %. Also, with the more probability of success, p, the both scheme's graphs don't have any difference.

Let's consider whether the redundancy made by the LNC scheme is truly an extra load. However, there is another factor that the LNC scheme improves the system's reliability with better PRR and reduced number of recovery processes. Therefore, we utilize a new design parameter, average number of effective transmissions which excludes counts of failed packets out of total number of packets unlike the average number of transmissions. In this case, as shown in Figure 19-21, the LNC scheme again outperforms the conventional routing one in terms of the average number of effective transmissions. It shows us that the LNC scheme is finally much more energy-efficient than the conventional one.

We have very similar simulation outcomes to the analytical results as shown in Figure 23-24. For simulations, we generate the random input channel for normalized p value with varying mean and standard deviation values as shown in Figure 22. With bigger standard deviations, the simulation results deviate further from the analytical results as we expected. Figure 23 shows us PRR for the LNC scheme and conventional routing one with both analytical results with straight lines and simulation results with dot lines. Also, Figure 24 shows us the average number of transmissions, E(TX), and the average number of effective transmissions, E(ETX) likewise.

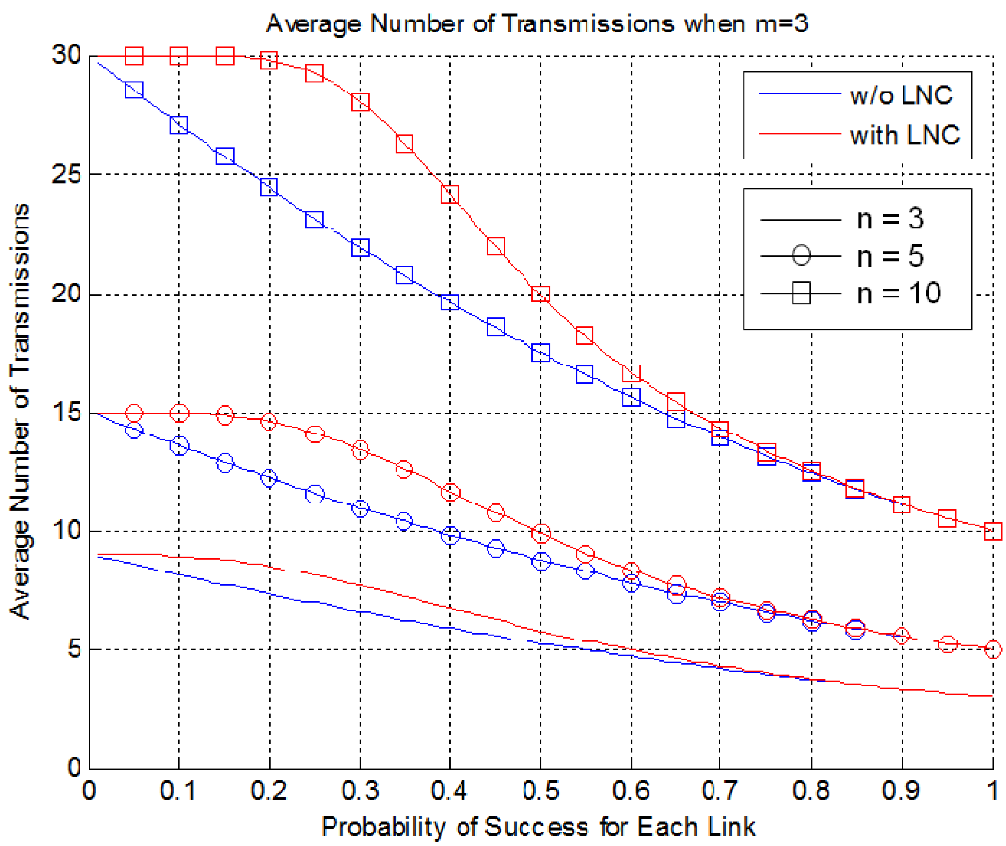


Figure 16 Average number of transmission when m = 3

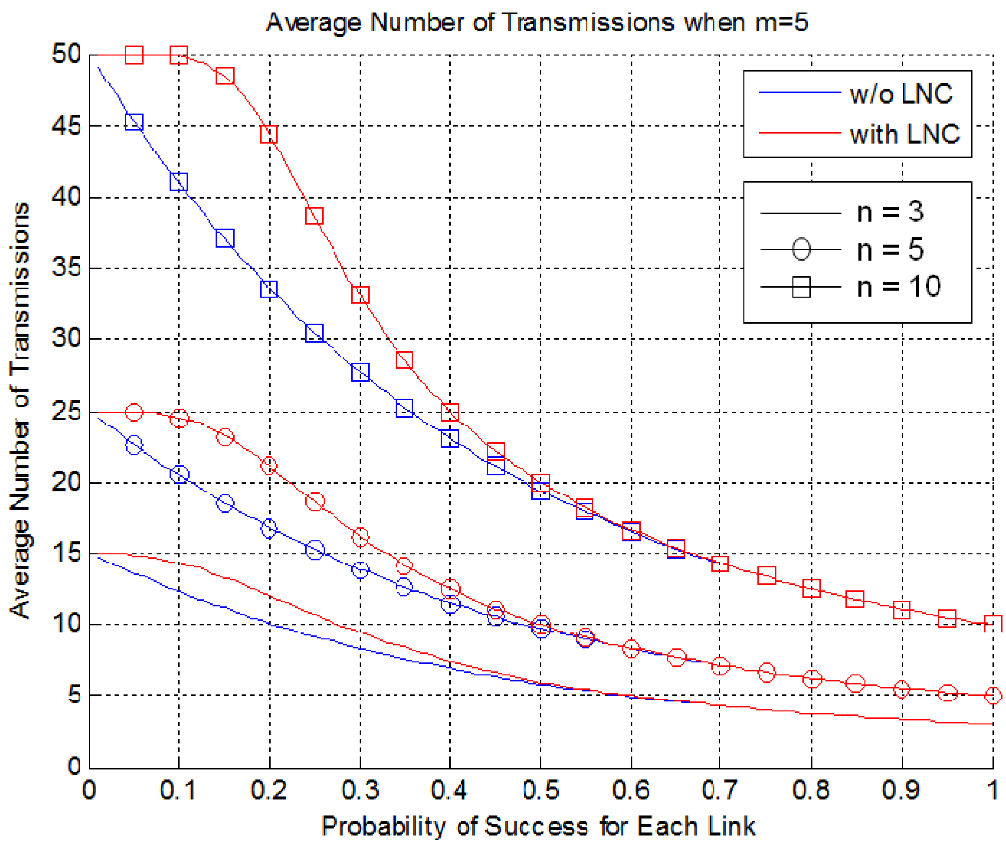


Figure 17 Average number of transmission when m = 5

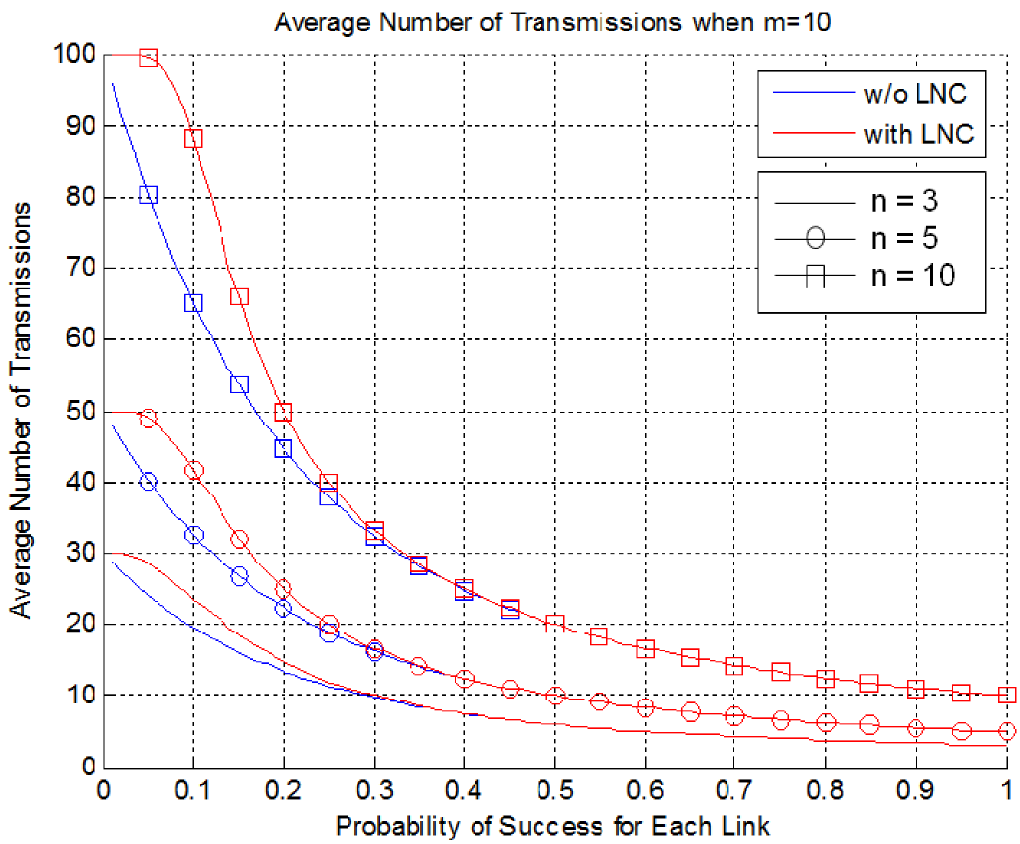


Figure 18 Average number of transmission when m = 10

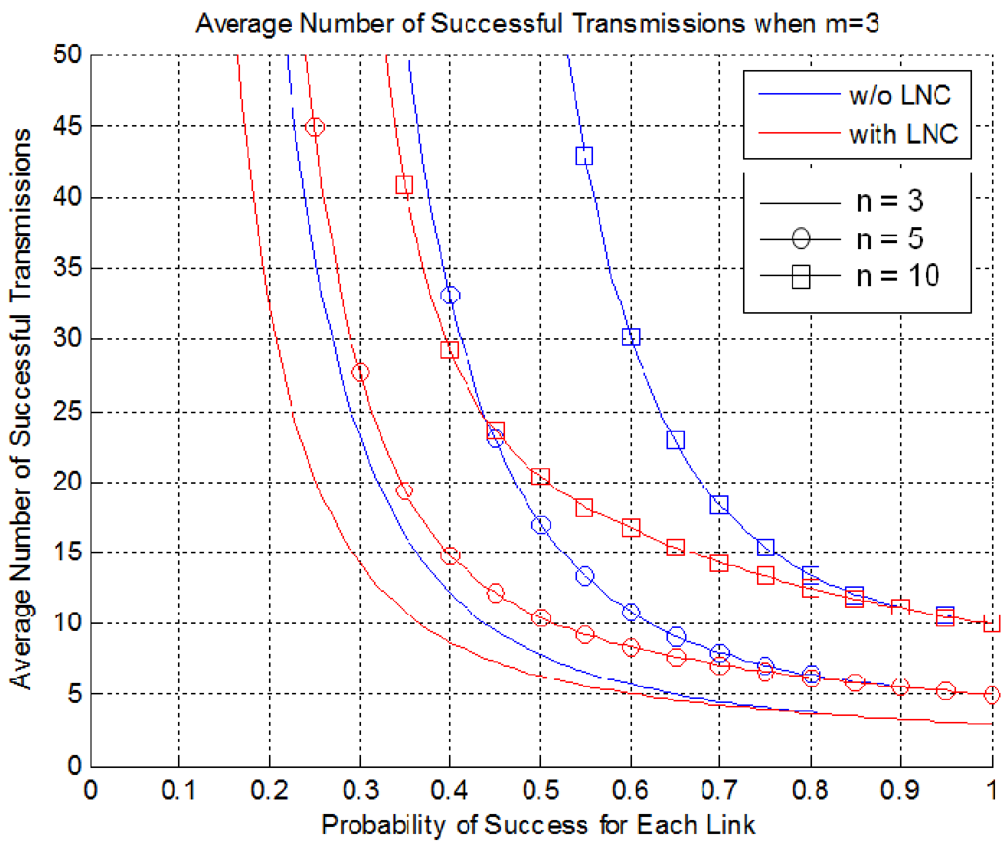


Figure 19 Average number of effective transmissions when m = 3

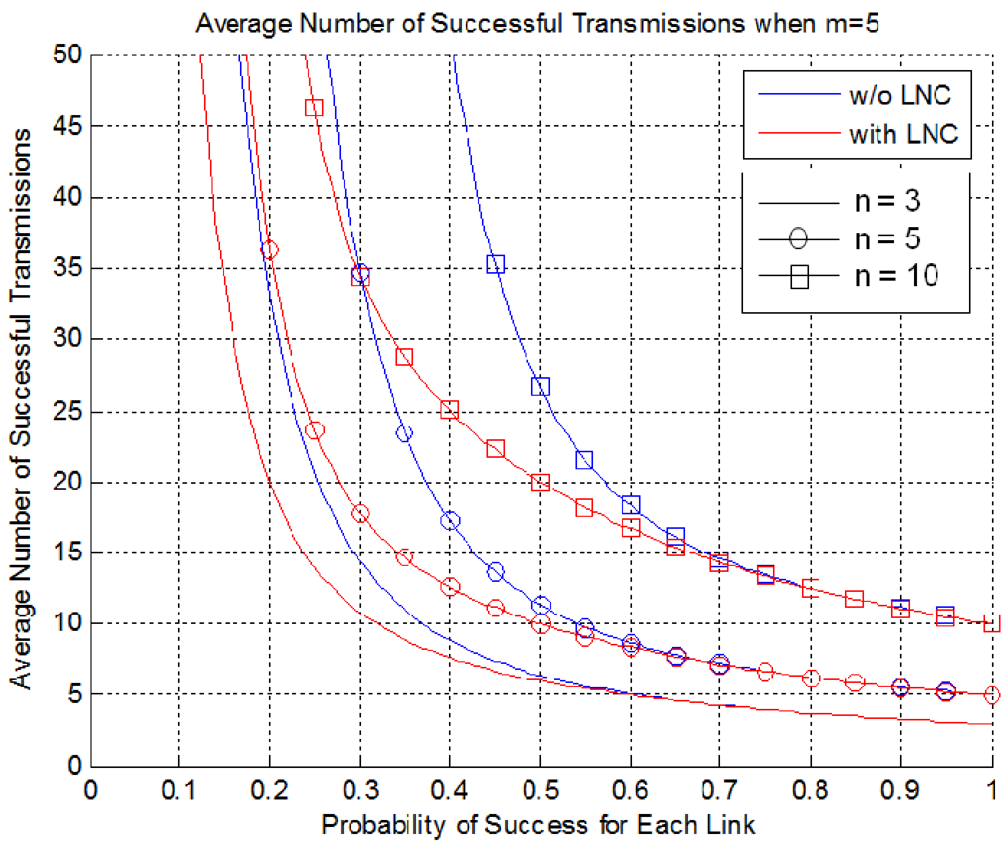


Figure 20 Average number of effective transmissions when m = 5

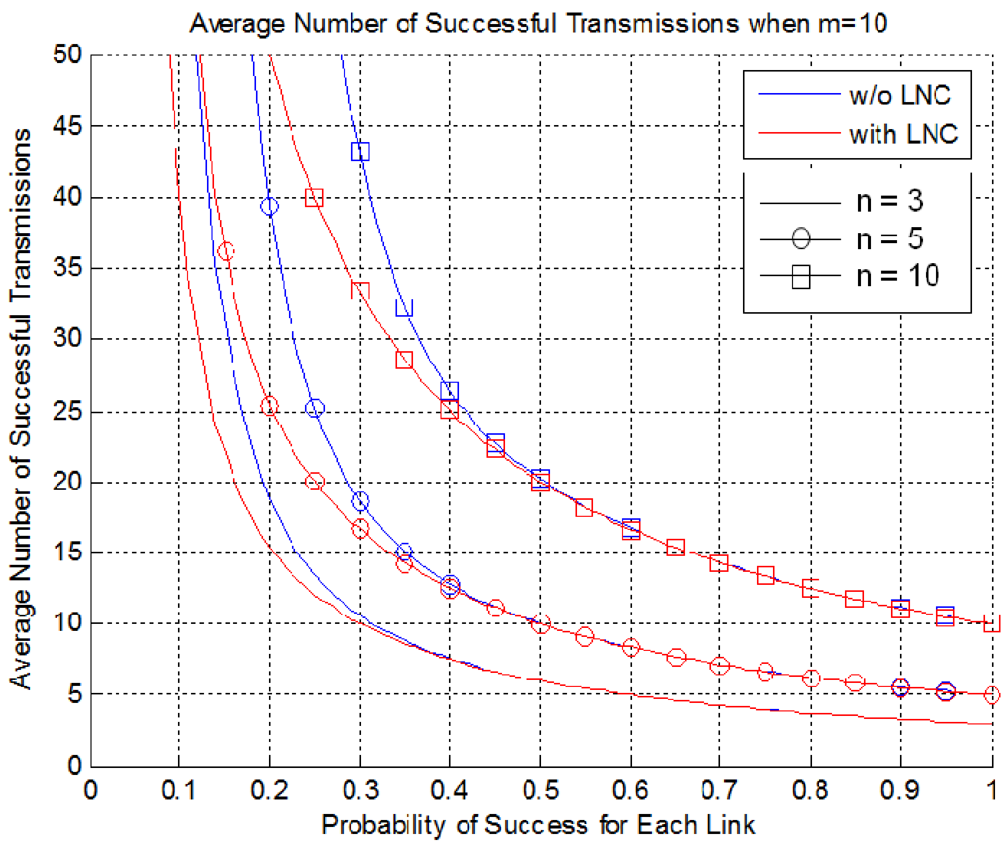


Figure 21 Average number of effective transmissions when m = 10

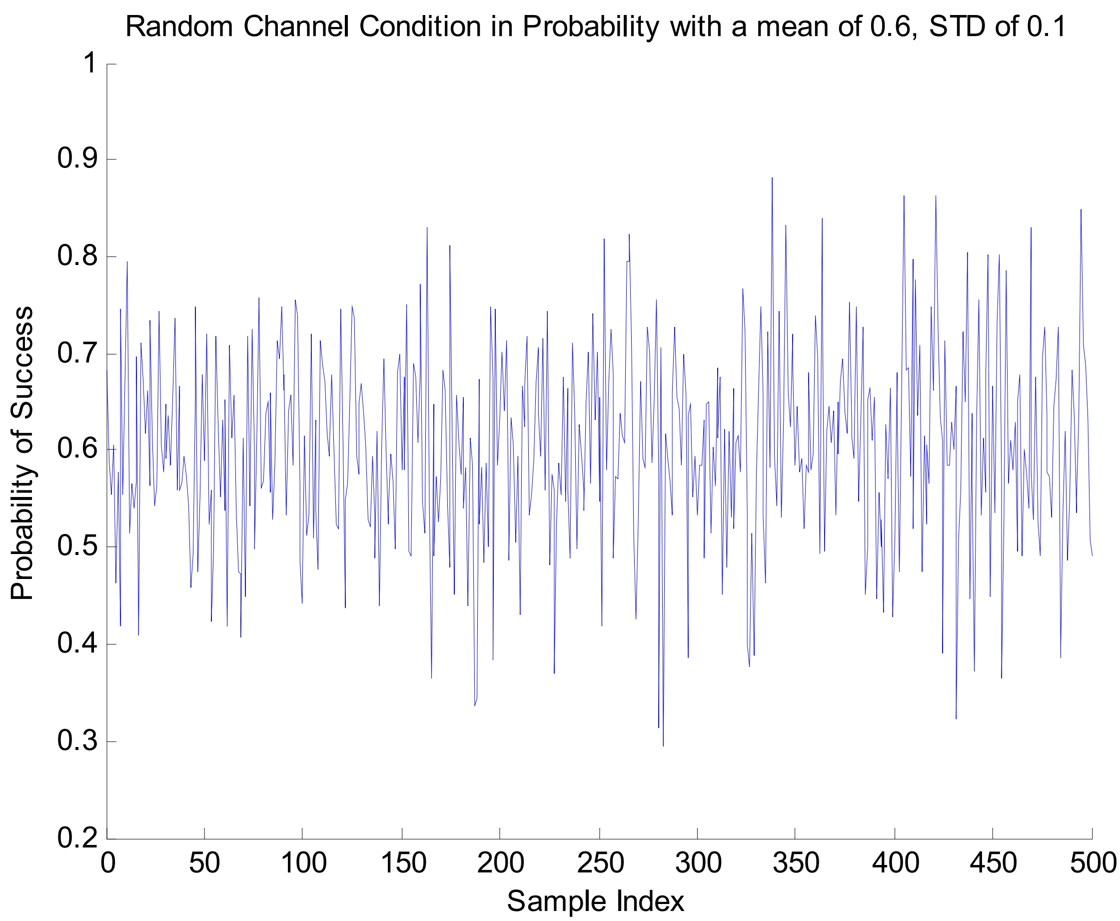
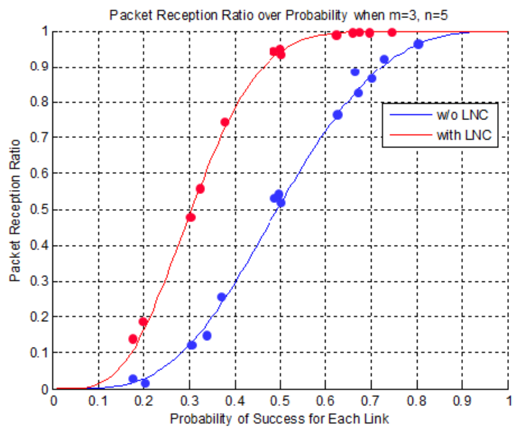
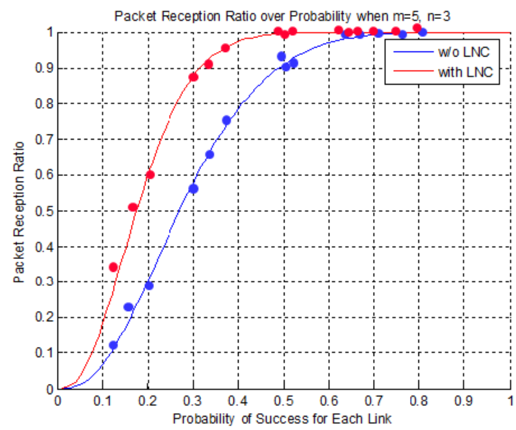


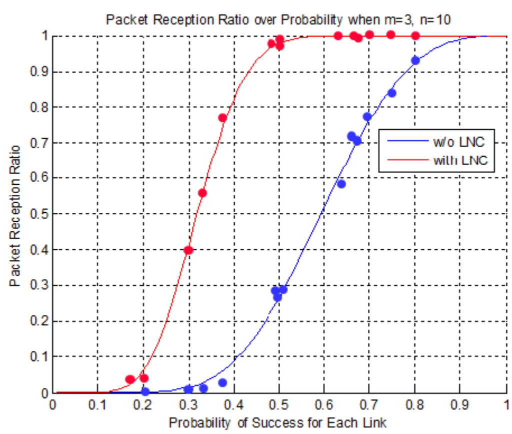
Figure 22 Random Channel Condition for a Simulation



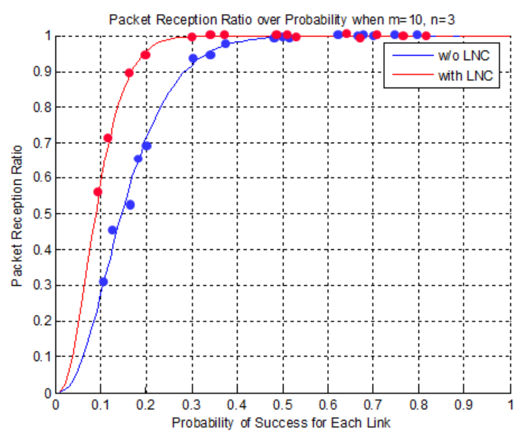
(a) when m=3, n=5



(b) when m=5, n=3

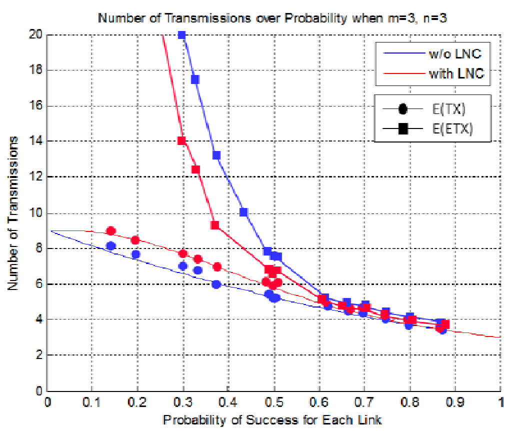


(c) when m=3, n=10

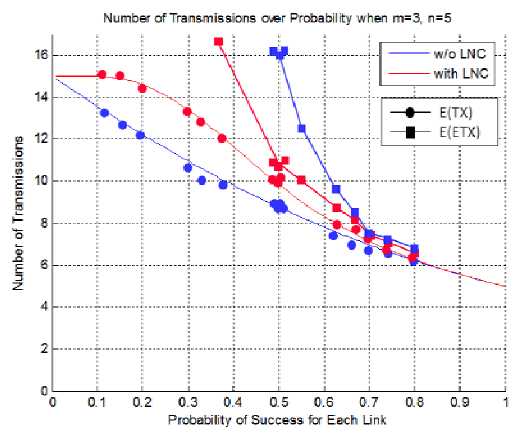


(d) when m=10, n=3

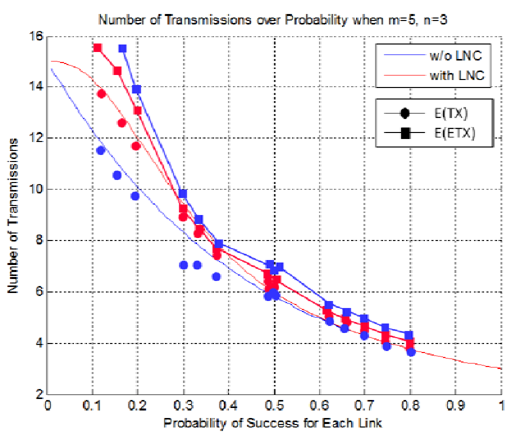
Figure 23 Simulation results: PRR



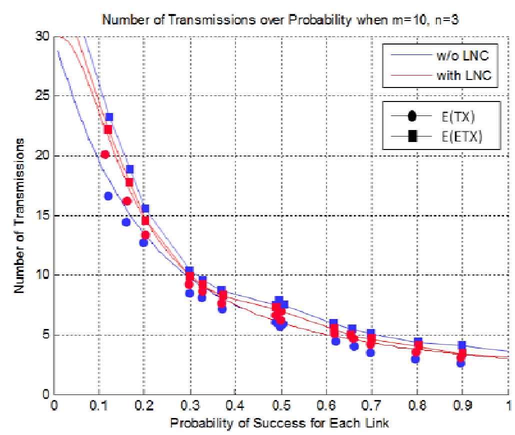
(a) when m=3, n=5



(b) when m=5, n=3



(c) when m=3, n=10



(d) when m=10, n=3

Figure 24 Simulation results: E(TX), E(ETX)

3. 5. Remarks

The proposed scheme with LNC always outperforms the conventional routing scheme in terms of PRR, which means that it has more reliability than the conventional one. In addition, the simulation results based on the comparisons of the average number of transmissions tells us that the redundant data transmission based on LNC is somewhat costly, but they have similar results when the probability of success is fairly high. However, the new design factor, the average number of effective transmissions, excludes the failed transmission from the total number of transmissions, and counts only the average number of transmissions out of successful transmission. This redefines how the design schemes are energy-efficient, and the LNC scheme again outperforms the conventional one. Therefore, the proposed LNC scheme outperforms the conventional routing one in terms of both reliability and energy-efficiency at the same time.

CHAPTER 4

Related Works

In the last few years, the most popular topics of researches related to wireless body area networks are reliable and energy-efficient design strategies since they are key issues of WBAN with limited resources. Those kinds of attempts have been very active and spread onto various abstract levels, technologies, and layers of approaches.

The research based on MAC technology has been one of the most popular topics in WBAN recently. Due to its simple and affordable network architecture, CSMA/CA was chosen for the first generation of WBAN. However, it has a fatal problem with power consumption since the system is supposed to listen to the link all the time. Furthermore, the bandwidth utilization was poor and it only deals with low traffic. Therefore, TDMA was selected for WBAN, and has still been the most popular MAC technology due to its low power consumption, high bandwidth utilization, and traffic handling. [36-39]

In addition, a number of hops and relay concept in networks have been challengeable research problems issued in wireless body area networks. Since human body is comparatively smaller than any other system's scale, single-hop networks were introduced at the beginning phase of wireless body area networks. However, excessive energy consumption was observed due to significant path loss of a human body which is 2 or 3 times bigger than normal air interface. Also, multi-hop networks were known as not energy-efficient network architecture since the hotspots appeared near the sink, which resulted in excessive battery usage problems at the specific nodes. Therefore, relay devices or cooperative approach become popular for WBAN in terms of energy-efficiency. [41-43]

CHAPTER 5

Summary, Conclusions and Future Research

In this dissertation, two different, but related research approaches are introduced. The first one is a dynamic load-balancing aware design supplementing the obsolete feedback of legacy optimal routing. The proposed scheme is examined targeting general multi-path routed networks with a view of network layer. This research is valuable for initial study approach for wireless networks since it is not limited to the type of application or specific systems. The second research direction is linear network coding application to wireless body area networks for healthcare systems. We narrow down the wireless technology from wireless networks to wireless body area networks, and also focus on the type of application from general sensor network systems to healthcare systems. The latter is examined for the reliability and energy-efficiency of wireless body area networks in terms of both network layer and MAC layer to verify how the design strategies reach the goal.

5. 1. Summary and Conclusions

First, we examined there is no true optimal routing design in wireless networks systems. The proposed scheme utilizes single design parameter, end-to-end delay, which can simplify and reduce the complexity of design and processing. It also presents a dynamic load-balancing aware model, and implements a practical model under the desired constraints.

In this study, we proposed an innovative multipath routing network design scheme utilizing dynamic load-balancing aware feedback control system which can predict future traffic flow with preloaded traffic control. In this system, we emphasized end-to-end delay, which is only used for a design parameter, as a means for coping with limited resources on sensor platforms. In addition, we implemented a practical model under the desired constraints based on the derived analytical model, and verified that the proposed scheme can enhance network performance in terms of balanced load, mean system delay, and overall end-to-end delay.

The second proposed design scheme with linear network coding application can improve the reliability without much cost of redundant packet transmission. We verify that the proposed scheme always outperforms the conventional routing scheme in terms of packet reception ratio (PRR). Furthermore, it can contribute energy efficiency by utilizing redundant packets to enhance the data transmission rate of success.

We also proved that the proposed scheme improves the energy efficiency by reducing the average number of effective transmissions per frame over the conventional routing scheme. Both network and MAC layers are considered as design strategies to achieve the reliability and energy-efficiency supplementing weak points of TDMA technology in WBAN such as dynamic network change, topology dependence, etc.

5. 2. Suggestions for Future Work

This research can be extended in the following directions.

- Multiple patients' monitoring

The proposed scheme is intra-WBAN approach that deals with the inside of WBAN. With multiple numbers of patients, challenging issues that signal interference among patients can arise in the Inter-WBAN area. How to deal with placing different kinds of relay nodes with LNC would be challenging problems.

- Relay node placement to maximize LNC efficiency

We take an assumption that only single relay node is supposed to be between source nodes and a sink node since we try to simplify the topology of the design based on TDMA technology. The mixed placement of multiple relay nodes can improve the LNC efficiency while we come up with more challenging issues related to much more complicated LNC application onto series of relay nodes.

- Node mobility consideration

Time slot allocations among source nodes are supposed be mostly static based on TDMA technology, and so does the topology. However, the link structure of nodes on a human body can be changed or disconnected due to the postural mobility around joint area. Consideration of the nodal mobility can be challenging issues when reallocating the sequence of nodes, and it affect the LNC application mechanism in a MAC layer.

BIBLIOGRAPHY

[1] B. Krishnamachari, Networking Wireless Sensors, Cambridge University Press, 2005.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless sensor networks: a survey,” Computer networks, 2002

[3] T. Arampatzis, J. Lygeros, S. Manesis, “A survey of applications of wireless sensors and wireless sensor networks,” Intelligent Control, 2005.

[4] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, J. Anderson, “Wireless sensor networks for habitat monitoring,” ACM International Workshop on Wireless Sensor Networks and Applications (WSNA'02), 2002.

[5] A. Cerpa, J. Elson, D. Estrin, L. Girod, M. Hamilton, J. Zhao, “Habitat monitoring: Application driver for wireless communications technology,” Proceedings of the 2001 ACM SIGCOMM Workshop, 2001.

[6] H. Wang, J. Elson, L. Girod, D. Estrin, K. Yao, “Target classification and localization in habitat monitoring,” Proceedings of the IEEE ICASSP, 2003.

[7] E. Biagioni, K. Bridges, “The application of remote sensor technology to assist the recovery of rare and endangered species,” Special issue on Distributed Sensor Networks for the International Journal of High Performance Computing Applications, 2002.

[8] E. Biagioni, G. Sasaki, “Wireless sensor placement for reliable and efficient data collection,” Proceedings of the Hawaiii International Conference on Systems Sciences, 2003.

[9] D. C. Steere, A. Baptista, D. McNamee, C. Pu, J. Walpole, “Research challenges in environmental observation and forecasting systems,” Proceedings of the sixth annual international conference on Mobile computing and networking, 2000.

[10] I. F. Akyildiz, T. Melodia, K. R. Chowdhury, “A survey on wireless multimedia sensor networks,” Computer Networks, 2007

[11] K. Akkaya, M. Younis, “A survey on routing protocols for wireless sensor

networks," Ad Hoc Networks 3, 2005.

[12] J. N. Al-Karaki, A. E. Kamal, "Routing techniques in wireless sensor networks: a survey," IEEE Wireless Communications, 2004

[13] K. Akkaya, M. Younis, "A survey on routing protocols for wireless sensor networks," Ad Hoc Networks, 2005

[14] S. Mueller, R. P. Tsang, D. Ghosal, "Multipath routing in mobile ad hoc networks: issues and challenges," Lecture Notes in Computer Science, 2004.

[15] P Sambasivam, A Murthy, EM Belding-Royer, "Dynamically adaptive multipath routing based on AODV," Proceedings of 3rd Annual Mediterranean Ad Hoc Networking, 2004.

[16] M. R. Pearlman, Z. J. Haas, P. Sholander, S. S. Tabrizi, "On the impact of alternate path routing for load balancing in mobile ad hoc networks," Mobile and Ad Hoc Networking and Computing, 2000.

[17] G. Parissidis, V. Lenders, M. May, B. Plattner, "Multi-path routing protocols in wireless mobile ad hoc networks: A quantitative comparison," Lecture Notes in Couputer Science, 2006.

[18] P. P. Pham, S. Perreau, "Performance analysis of reactive shortest path and multi-path routing mechanism with load balance," Proceedings of IEEE Infocom, 2003.

[19] Y. Ganjali, A. Keshavarzian, "Load balancing in ad hoc networks: single-path routing vs. multi-path routing," INFOCOM 2004.

[20] H. Pucha, Y. Zhang, Z. M. Mao, Y. C. Hu, "Understanding network delay changes caused by routing events," Proceedings of the 2007 ACM SIGMETRICS, 2007.

[21] S. Roy, D. Saha, S. Bandyopadhyay, T. Ueda, S. Tanaka, "Improving end-to-end delay through load balancing with multipath routing in ad hoc wireless networks Using Directional Antenna," Lecture Notes in Computer Science, 2003.

[22] S. J. Lee, M. Gerla, "Dynamic load-aware routing in ad hoc networks," ICC, 2001.

[23] W Leland, TJ Ott, "Load-balancing heuristics and process behavior," ACM SIGMETRICS, 1986.

[24] D. Bertsekas, R. Gallager, Data Networks, Prentice Hall, Saddle River, 1992.

[25] Z. Zhao, Y. Shu, L. Zhang, H. Wang, O. Yang, “Flow-level multipath load balancing in MPLS network,” IEEE International Conference on Communications, 2004.

[26] L. Zhang, Z. Zhao, Y. Shu, L. Wang, O. Yang, “Load balancing of multipath source routing in ad hoc networks,” IEEE International Conference on Communications, 2002.

[27] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci “Wireless Sensor Networks: a Survey,” Computer Networks, 2002.

[28] K. Akkaya, M. Younis, “A Survey on Routing Protocols for Wireless Sensor Networks,” Ad Hoc Networks, 2005.

[29] J.N. Al-Karaki, A.E. Kamal, “Routing Techniques in Wireless Sensor Networks: a Survey,” IEEE Wireless Communications, 2004.

[30] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, V. Leung, “Body Area Networks: A Survey,” ACM/Springer Mobile Networks and Applications, 2010.

[31] H. Alemdar, C. Ersoy, “Wireless Sensor Networks for Healthcare: A Survey,”

[32] J. Ko, C. Lu, S.B Mani, J.A. Stankovic, A. Terzis, M. Welsh, “Wireless sensor networks for healthcare,” Proc. IEEE 2010.

[33] H. Alemdar and C. Ersoy, "Wireless sensor networks for healthcare: A survey," Computer Networks, 2010.

[34] M.A. Hanson, H.C Powell Jr., A.T. Barth, K. Ringgenberg, B.H. Calhoun, J.H. Aylor, J. Lach, “Body Area Sensor Networks: Challenges and Opportunities,” IEEE Computer, vol.42, 2009.

[35] K. Lorincz, D. Malan, T.R.F. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, M. Welsh, S. Moulton, “Sensor networks for emergency response: challenges and opportunities,” IEEE Pervasive Computing, 2004.

[36] B. Latre, B. Braem, I. Moerman, C. Blondia, E. Reusens, W. Joseph, P. Demeester, “A low-delay protocol for multi-hop wireless body area networks,” in Proc. 4th Int.

Conf., MobiQuitous 2007.

[37] B. Braem, B. Latre, C. Blondia, I. Moerman, P. Demester, “Improving Reliability in Multi-hop Body Sensor Networks,” Proc. 2nd Int’l. Conf. Sensor Tech. Apps., 2008.

[38] A.Ehyaei, M.R.Hashemi, P.Khadivi, "Using Relay Network to Increase Life time in Wireless Body Area Sensor Networks", Proceedings of IREHSS, 2009.

[39] B. Braem, B. Latre, I Moerman, C. Blondia, “The Wireless Autonomous Spanning Tree Protocol for Multihop Wireless Body Area Networks,” Annual International Conference on Mobile and Ubiquitous Systems, 2006.

[40] B. Otal, L. Alonso, C. Verikoukis, “Highly reliable energy-saving mac for wireless body sensor networks in healthcare systems,” IEEE Journal on Selected Areas in Communications, 2009.

[41] W. Ye, J. Heidermann, D. Estrin, “An Energy-Efficient MAC Protocol for Wireless Sensor Networks,” Infocom, 2002.

[42] S. Marinkovic, C. Spagnol, E. Popovici, “Energy-Efficient TDMAbased MAC Protocol for Wireless Body Area Networks”, Proceedings of the Third International Conference on Sensor Technologies and Applications, SENSORCOMM 2009.

[43] O. Omeni, A. C. W. Wong, A. J. Burdett, and C. Toumazou, “Energy efficient medium access protocol for wireless medical body area sensor networks,” *IEEE Trans. Biomed. Circuits Syst.*, 2008.

[44] S. Li, R. Yeung, N. Cai, “Linear Network Coding,” IEEE Transactions on Information Theory, 2003.

[45] C. Fragouli, J. Y. Boudec, and J. Widmer, “Network Coding: An Instant Primer,” ACM SIGCOMM Computer Communication Review, 2006.

[46] R. Koetter and M. Medard, “An algebraic approach to network coding,” IEEE/ACM Trans. Networking, 2003.

[47] C. Fragouli, J.Y. Le Boudec, J. Widmer, “Network Coding: an Instant Primer,” ACM SIGCOMM Computer Communication Review, 2006.

[48] T. Ho, M. Medard, R. Koetter, D.R. Karger, M. Effros, J. Shi, B. Leong, “A Random Linear Network Coding Approach to Multicast,” IEEE Transactions on Information Theory, 2006.

[49] S.K. Yoon, Z. Haas, “Application of Linear Network Coding in Delay Tolerant networks,” Ubiquitous and Future Networks (ICUFN, 2010.

[50] Z. Guo, B. Wang, and J.-H. Cui "Efficient Error Recovery Using Network Coding in Underwater Sensor Networks" Proceedings of IFIP Networking 2007.

glossary

802.15.6 IEEE working group researching Wireless Personal Area Networks (WPANs) as networks that operate in the vicinity of a person and a subset of these networks are Wireless Body Area Networks (WBANs) which operate in and around the human body

CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) Protocol used in Ethernet networks to ensure that only one network node is transmitting on the network wire at any one time

ECG (Electrocardiogram) A device used to measure electrical activity of the heart through a series of electrical leads placed on the skin

EEG (Electroencephalography) The recording of electrical activity along the scalp

EMG (Electromyography) a technique for evaluating and recording the electrical activity produced by skeletal muscles

MAC (Medium Access Control) Data communication protocol sub-layer below data link layer

PRR (Packet Reception Ratio) The ratio of successful reception over the total number of data transmission

TDMA (Time Division Multiple Access) Time divided channel access method

WISL (Wireless Intelligent Systems Laboratory) The research group of Dr. Stephen B. Wicker at Cornell University

WSN (Wireless Sensor Network) A collection of sensor equipped devices organized into a wireless network

WBAN (Wireless Body Area Network) A network equipped with sensors, transmission and relay nodes on a human body that monitors signals and communicates with a medical server

LNC (Linear Network Coding) A technique which combines input data for better reliability using linearly independent coefficients.